A Few Electron-Hole Semiconducting Carbon Nanotube Quantum Dot

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Abstract. Carbon nanotubes are ideal systems to explore the physics of 1-dimensional materials. At low temperatures carbon nanotubes exhibit a variety of phenomena, such as Coulomb blockade[1-4], quantum interference[5] and the Kondo effect[6]. So far these observations have been made mainly in metallic nanotubes. Of particular interest is the study of electronic transport in nanotube quantum dots, where information about the quantized energy levels can be obtained. Despite some studies at intermediate temperatures[7], semiconducting nanotube single quantum dots have been proven difficult to realize at low temperatures preventing, for example, the observation of the electronic spectrum. Here we show that semiconducting individual single-walled carbon nanotubes can behave as fully coherent single quantum dots operating both in the few-electron and few-hole regime. We find that the discrete excitation spectrum for a nanotube with *N* holes is strikingly similar to the corresponding spectrum for *N* electrons. The data indicate a near-perfect electron-hole symmetry as well as the absence of scattering in semiconducting carbon nanotubes.

The fabrication of the devices follows those of refs [8,9]. Basically, HiPco nanotubes[10] are deposited from a suspension onto an oxidized Si substrate. Individual nanotubes are located with an atomic force microscope and electrically contacted by source and drain Cr/Au electrodes (Fig. 1a). The highly doped Si serves as a backgate. We then suspend the nanotubes by etching away part of the SiO_2 surface[9]. We generally find that removing the nearby oxide reduces the amount of potential fluctuations (i.e. disorder) in the nanotubes, as deduced from transport characteristics.

A low-temperature measurement around zero gate voltage (Fig. 1b) shows a large zero-current gap of about 300meV in bias voltage, reflecting the semiconducting character of this nanotube. The zigzag pattern outside the semiconducting gap is due to Coulomb blockade. These Coulomb blockade features are more evident in Fig. 1c, where a high-resolution measurement of the differential conductance shows the semiconducting gap with the first two adjacent Coulomb blockade diamonds. These correspond to a single electron (right) and a single hole (left), demonstrating that semiconductor nanotubes can operate as single electron transistors in the single electron and single hole regime[1].

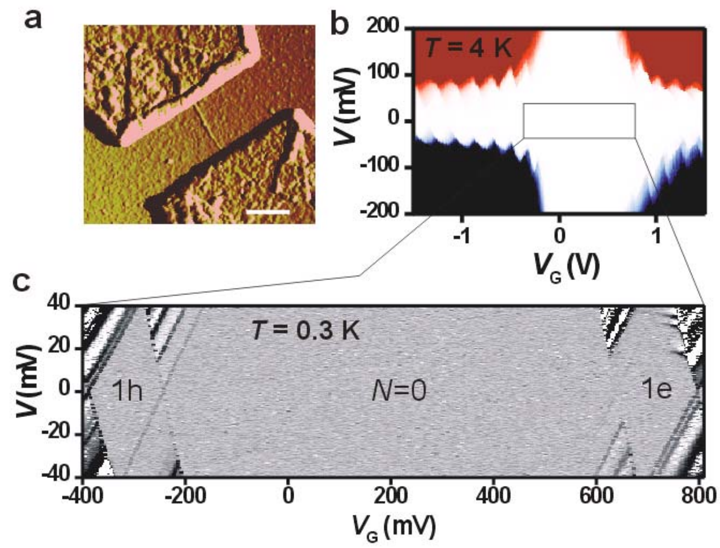

FIGURE 1. a, AFM picture of the device. b, Current vs bias and gate voltage. c, Conductance vs bias and gate voltage, showing the single electron and single hole region.

Fig. 2a shows the filling of the QD, one by one, up to hole number 20. The region for the first 2 holes is enlarged in Fig. 2b. The regularity in the Coulomb diamonds indicates a nanotube that is free of disorder. A closer inspection shows that the size of the Coulomb diamonds varies periodically on a smooth background as the hole number increases (Fig. 2c). The alternating, even-odd pattern in this addition energy, E_{add}, reflects the subsequent filling of discrete orbital states with two holes of opposite spin[1,4].

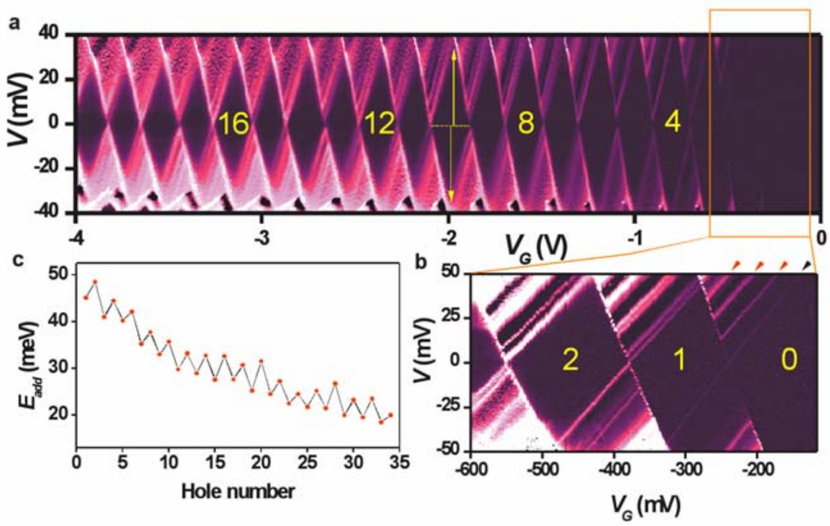

FIGURE 2. a, Stability diagram in the few-hole region. b, Region corresponding to 0-2 holes. Excitation lines can be seen. c, Addition energy as a function of hole number.

The additional discrete lines outside the Coulomb diamonds running parallel to its edges correspond to transport through excited states[1], as for instance indicated by arrows in Fig. 2b. This excitation spectrum can be measured both for electrons and holes. Fig. 3 shows this comparison for the Coulomb diamonds corresponding to 1-2 holes and 1-2 electrons. Remarkably, the excitation spectrum is nearly identical. The observation of electron-hole symmetry poses severe restrictions on the QD system: the effective masses for holes and electrons should be equal and the QD should be free of disorder. Scattering by negatively charged impurities, for example, is repulsive for electrons but attractive for holes, so it would break electron-hole symmetry. A symmetric band structure has been theoretically predicted for graphite materials and carbon nanotubes[11]. In contrast, the absence of scattering has come as a positive surprise.

The observation of the quantum properties of semiconducting carbon nanotubes opens the way to both fundamental and applied research on one of the potentially most relevant materials in the technology at the nanoscale.

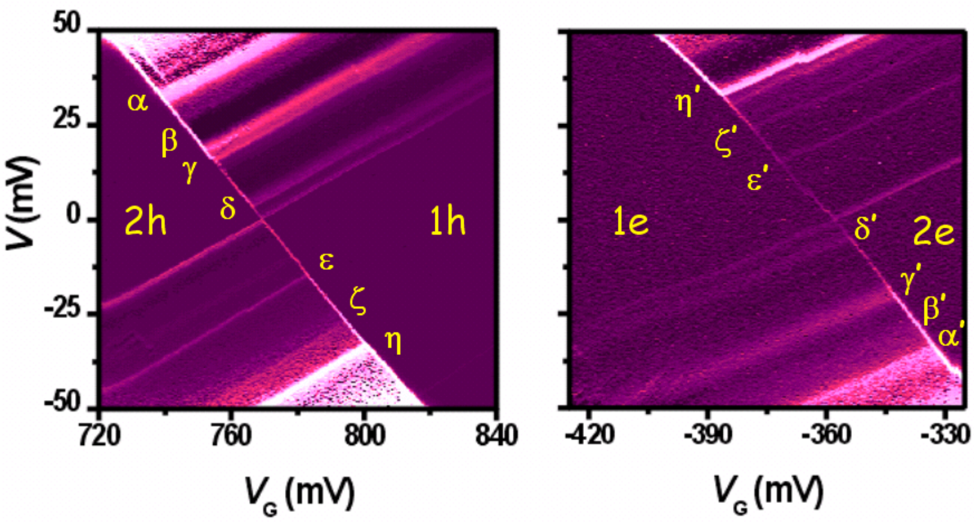

FIGURE 3. Stability diagram showing the symmetric spectrum for electron and holes.

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